Seismic Studies of the Caspian Basin and Surrounding Regions

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Grant No. F49620-92-J-0475 (AFOSR) and Grant Pending (DOE)

Abstract:

The crust and upper mantle structure of the south Caspian Basin and the Turkmenian Lowlands is enigmatic. From Soviet deep seismic sounding data collected in the 1960's, the crust appears to consists of two layers: a thick sedimentary section (15–25 km) with low P–wave velocity (3.5–4.0 km/s) overlying a 12–18 km thick basaltic lower crust. It has been suggested that this basaltic lower crust is "oceanic–like" crust and that the south Caspian Basin represents a section of relic ocean from a Paleozoic – Triassic ocean or a Mesozoic – Paleogene marginal sea. Improved knowledge of the crust and upper mantle velocity structure of the south Caspian Basin is important in a seismic verification context because of the anomalous effect it has on regional seismic waveforms. To investigate the crust and upper mantle structure of the south Caspian Basin, we have installed six three–component seismograph stations within the former Soviet Republics of Turkmenia and Azerbaijan. Our objective is to determine the velocity structure of this region using both body wave receiver function and surface wave modeling techniques. We present receiver function inversion results for four sites and fundamental mode Rayleigh wave observations for two great circle paths across this region.

Key Words: South Caspian Basin, crust and upper mantle structure, receiver functions, surface wave dispersion

Objectives:

The objective of the research funded by the existing AFOSR grant is to develop models for the crust and upper mantle velocity structure of the south Caspian Basin using body wave receiver function and surface wave dispersion techniques. To accomplish this we have installed six digital three–component seismic stations in the former Soviet republics of Turkmenia and Azerbaijan and have operated these for almost two years. The research objectives of the pending DOE grant are to utilize the seismic data collected under the AFOSR grant and the seismic velocity models developed for the south Caspian Basin for seismic event characterization, regional wave propagation, and discriminant transportability in the Middle East.

Preliminary Research Results and Research Accomplished:

The south Caspian Basin and the Turkmenian Lowlands form an anomalous aseismic depression that is bounded to the north by the Apsheron–Balkhan Sill, a narrow seismogenic zone extending from the Caucuses Mountains in Azerbaijan to the Kopet Dagh Mountains of Turkmenia; and to the west in Azerbaijan and to the south along the Iranian border by the active fold and thrust belts of the Talesh and Alborz Mountains, respectively. The northward movement of the Iranian plate with respect to the Eurasian plate is causing compressional deformation throughout the Caspian region (Jackson and McKenzie, 1984). Mechanisms of earthquakes occurring within the bounding seismic belts of the south Caspian Basin suggest that the crust of the south Caspian Basin is being overriden by the continental crust of the Iranian plateau in the south, and to a lesser extent, by the northern Caspian continental crust (Priestley et al, 1994). In addition, the velocity structure of the south Caspian Basin is poorly known. Deep seismic sounding data collected in the early 1960's suggests that the crust of the south Caspian Basin and west Turkmenian Lowlands consists of two layers: a thick sedimentary layer (15–20 km) with a P–wave velocity of 3.5–4.0 km/s which overlies a 12–18 km thick "basaltic" layer with a P–wave velocity of 6.6–7.0 km/s (Neprochnov 1968; Rezanov and Chamo, 1969). It has been suggested that the south Caspian Basin represents a section of "ocean–like" crust that may be either a relic of an older Paleozoic–Triassic ocean, or a marginal sea which developed behind a Mesozoic–Paleogene ocean (Berberian and King 1981; Berberian 1983). The south Caspian Basin strongly affects the propagation of regional seismic waves. For example, the seismic phase Lg is blocked for paths crossing the south Caspian Basin (Kadinsky–Cade et al, 1981). This has important ramifications for seismic monitoring in the Middle East.

The Caspian Seismic Network: To better understand the crust and upper mantle structure in the south Caspian region and its effect on regional seismic wave propagation, we have installed six, three–component broadband digital seismographs around the south Caspian Sea in the former Soviet republics of Turkmenia and Azerbaijan (Fig. 1). The Turkmenian stations are located near Krasnovosdk (KRV), Nebit Dag (NBD), Dana Tag (DTA) and Kizyl Atrek (KAT); the Azerbaijan the stations are located near Lenkoran (LNK) and Baku (BAK). In June 1994 BAK was relocated 100 km west to Shemaha (SHE). The Turkmenian stations are operated in cooperation with Dr. B. Karryev from the Institute of Seismology of Turkmenia, and the Azerbaijan stations are operated in cooperation with Dr. S. Agamirzoev from the Geophysical Expedition of Azerbaijan. Dr. Mikhail Rozhkov of SYNAPSE oversees the station operation from Moscow. Data at each site is recorded on a Refraction Technology 72a–02 data logger that is equipped with either

Omega or GPS timing. Stations KRV, DTA, KAT and LNK have Guralp CMG–3T sensors and stations NBD, BAK and SHE have Geotech SL–210/220 long period sensors. All stations record data continuously at 10 samples per second and some have a triggered data stream at 50 samples per second. We are calibrating each station with a pseudo–random binary input on an annual basis and with a step function at each station visit ($\sim$ 6 weeks). Data is received at Cambridge from Moscow six to nine months after recording.

Analysis of Teleseismic Body Waves: We are using teleseismic body waves to determine the velocity structure beneath the CSN stations and the IRIS station ABKT (Fig. 1). We have measured the backazimuth of the teleseismic P–waves as a function of frequency using a maximum likelihood (Harris, 1990) and multi–taper (Park et al, 1987) approach to determine the magnitude of scattering in the teleseismic P–waveform at each site. This comparison shows that, except at KRV, the majority of the scattering occurs at high frequency ($> \sim 0.5Hz$), which provides a guide in the receiver function analysis.

For each Caspian station we isolated the P to S converted phases in the 30 seconds following the P–wave arrival using the source equalization method (Langston, 1979; Ammon, 1991). Receiver functions were computed to include frequencies up to 0.4 Hz and only the most stable deconvolutions (those with averaging functions that approximate a narrow band Gaussian pulse) were used to infer structure. Events from common source regions were stacked and the variance of the stacked data is used as a measure of coherence of individual Ps arrivals. We studied the response by examining the radial and tangential components as a function of azimuth, and determined a 1–D estimate of the receiver structure using the receiver function inversion method of Ammon et al. (1990). Figure 2 shows the model solutions for ABKT, KRV, NBD, and LNK.

ABKT is located 400 km east of the south Caspian Basin in the Kopet Dag Mountains. The velocity models show a relatively simple structure compared to the south Caspian Basin models. The crust can be divided into two layers separated by a prominent 1 km/s step in velocity between 16–20 km depth. The upper–crust between 2–16 km depth has an average velocity of 5.75 km/s. The lower crust between 20–38 km depth has an average velocity of 7.1 km/s. The crust–mantle transition is gradational and the upper–mantle has a P–wave velocity 8.2 km/s. KRV is located on the eastern shore of the Caspian on the trend of the Apsheron–Balkhan Sill. The velocity models have a strong gradient from 3.7 km/s at the surface to 4 km depth. Between 4 and 17 km depth the average velocity is 6.5 km/s. A step in velocity occurs from 17–21.5 km depth. This very thin crust overlies a relatively constant upper–most mantle with an average velocity of 7.9 km/s. NBD is the only site which may be located within the "ocean–like" crustal region. The velocity models are based on only two events; however, the particle motion between the radial and tangential receiver functions indicate little scattered energy. The shallow crust has a strong gradient from 3.1 km/s at the surface to 7.2 km/s at to 6 km depth. Beneath this layer the average velocity is 5.6 km/s between 10–20 km depth. A step in velocity is present at 20 km depth (similar magnitude to ABKT), followed by a positive gradient that reaches 8.0 km/s at 38–40 km depth. LNK is along the southwestern shore of the Caspian Sea, in the foothills of the Talesh Mountains. The velocity models show a low–velocity upper crust varying from 2.25 km/s at the surface to 4.1 km/s at 6 km depth. Starting at 6 km depth there is a strong positive gradient with a velocity of 7.2 km/s at 12 km depth. Below this the velocity is high but does not reach an upper mantle velocity of 8.0 km/s at 50–52 km depth.

The velocity models beneath each station are considerably different. For KRV, NBD and LNK,

the shallow low velocity upper crust fits the delay of the first pulse on the radial component with respect to the direct P–wave arrival on the vertical component. This delay is not present in the ABKT data. This low velocity uppermost crust is consistent with a sedimentary layer, but beneath NBD it is much less than the previously reported 15–20 km thick. Only at LNK is a relatively thick sedimentary pile present. The 7.2 km/s layer between 6–10 km depth beneath NBD is the most prominent feature of all Caspian models. The velocity of this layer is consistent with ultra–mafic rock velocities and may represent the remnant oceanic crust. It is unlikely that this layer has remained laterally continuous throughout the Turkmenian Lowlands since emplacement, given the level of scattering observed at KAT, where we have so far been unable to obtain a physically realistic 1–D model estimate.

Surface Wave Analysis: The study of Kadinsky–Cade et al. (1981) demonstrated that the seismic phase Lg is largely blocked for paths crossing the south Caspian Basin and this is also apparent in the data we have collected in the region immediately surrounding the Caspian. However, Figure 3 shows that the south Caspian Basin also severely disrupts low frequency fundamental mode surface wave trains. Figure 3a compares broadband seismograms for a mid–Atlantic ridge earthquake propagating along a great circle path between LNK and KAT. The LNK seismogram shows a dispersed fundamental mode wave train ($\sim$ 2400–3000 seconds) followed by scattered surface wave arrivals. The lowest frequency fundamental mode surface wave arrival seen in the LNK seismogram is clear in the KAT seismogram ($\sim$2600–2700 seconds) but the dispersed wave train observed at LNK is largely missing from the KAT seismogram and the overall surface wave amplitude has decreased significantly. Figure 3b compares seismograms for a north Mulucca Sea earthquake propagating along a great circle path between KAT and LNK, i.e., reversing the path of the event in Figure 3a. These seismograms exhibit the same degradation of the surface wave train and show that this is not, for example, an instrumental effect. We have observed this phenomenon for all events propagating along great circle paths across the central portion of the south Caspian Basin.

The great circle path between KRV and KAT crosses the Turkmenian Lowlands. Russian earth scientists have suggested that this region is structurally part of the south Caspian Basin and that the crust in the region consists of 10–15 km of sediment lying on "ocean–like" crust. The deep thickness of sediments is verified from well logs (Sengor, personal communications, 1995). Surface waves propagating along the KRV–KAT great circle path do not show the same disruption (Fig. 4a) as those propagating across the main part of the basin (Fig. 3). Figure 4b shows the fundamental mode Rayleigh wave phase velocity dispersion curve for this path. This curve was computed from four seismogram pairs using a constrained least–squares algorithm (Gomberg et al, 1988). The KRV–KAT phase velocity curve is compared with observed dispersion curves for an ocean basin (Kuo et al, 1962) and a continental tectonic (Knopoff et al, 1966) region. The KRV–KAT phase velocity is high for periods greater than 40 seconds and exceptionally low for periods less than 30 seconds. We do not feel comfortable in interpreting the KRV–KAT phase velocity curve at this time until we have included the past year's data which we have recently received.

Effects on Regional Wave Propagation: The velocity structures from body wave modeling provide some insight of the effects of crustal structure on regional seismic waves propagating across the south Caspian Basin. It is clear from the Caspian data that both longer and shorter

period surface wave trains are greatly scattered or attenuated for travel paths across the Caspian Sea, and to a lesser degree for paths across the Turkmenian Lowlands. The Lg phase is blocked for travel paths across oceanic crust, as well as in regions where the crustal structure includes rapid changes in thickness. If we consider the Lg phase to consist of multiple reflected S waves trapped within the crustal wave guide, then the receiver function modeling results suggest that the blockage is due to the abrupt change in crustal structure from a relatively simple model beneath ABKT to complex models beneath NBD and LNK. Although these are 1–D models and the basin is a 3–D structure, these observations support a scattering mechanism. Recent analysis of the logarithmic rms amplitude ratio of Sn/Lg (Zhang and Lay 1994) has shown that this ratio can be linearly related to changes in surface topography. The southern margins of the Basin and the eastern margin of the Turkmenian Lowlands range from below sea level at LNK up to 2 km in the Alborz Mountains. These features probably contribute to the Lg blockage, but these effects have not been examined to date.

Recommendations and Future Plans:

The research focus under the existing AFOSR grant is for the operation of the digital seismographs in the region surrounding the south Caspian Basin and the analysis of the teleseismic body wave and surface wave data to determine the velocity structure of the crust and upper mantle. Our study has shown that the south Caspian has an anomalous crustal structure and this has a pronounced effect on not only higher frequency regional seismic waveforms but also lower frequency surface waves. The research focus of our new grant will be to use this structural information and the data recorded on the CSN and other seismograph stations in the Middle East to improve understanding of (1) the crust and upper mantle velocity structure of the region south of the Caspian, (2) the amplitude and frequency characteristics of regional seismic phases Pn, Pg, Sn, and Lg, and (3) the source characteristics of moderate size seismic events in the region surrounding and to the south of the Caspian Sea.

We intend to continue work on the crustal structure of the Caspian Basin. Much of our current knowledge of the crustal structure of the south Caspian Basin has come from analyses of Soviet DSS data collected primarily in the 1960's. Little of this data has been available to western seismologists. We have recently obtained funds to digitize these data and reinterpret them with more modern techniques than those available to Soviet seismologists in the 1960's. This work should commence this autumn. While these data are not of comparable quality to modern refraction data, they should help in understanding the crustal structure of this anomalous region.

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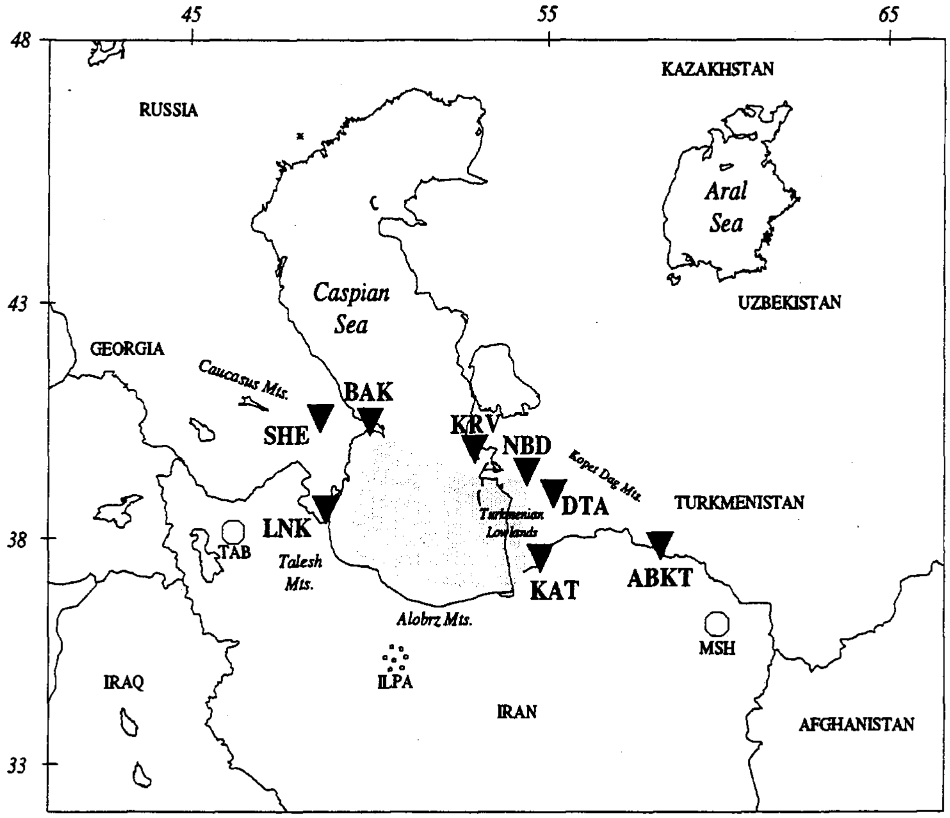


Figure 1. Caspian Seismograph Network stations Krasnovosdk (KRV), Nebit Dag (NBD), Kizyl Atrek (KAT), Dana Tag (DTA), Lenkoran (LNK), Baku (BAK) and Shemaha (SHE). Also shown are WWSSN stations TAB and MSH, the Iranian Long Period Array (ILPA) and IRIS station ABKT. The shaded region denotes the subsurface lateral extent of the suspected "ocean-like" crust.

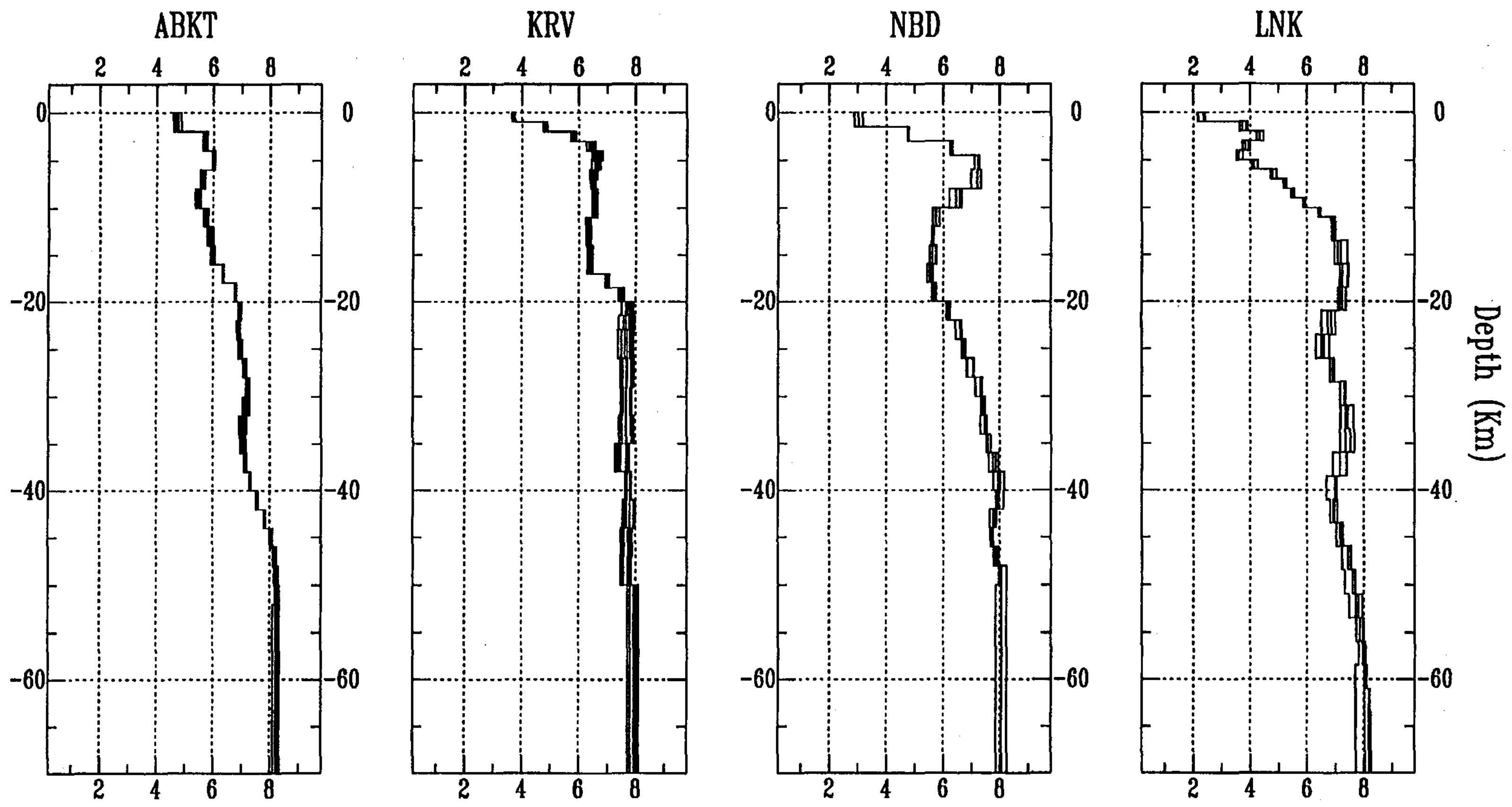


Figure 2. P-wave velocity receiver function modeling results for stations ABKT, KRV, NBD, and LNK

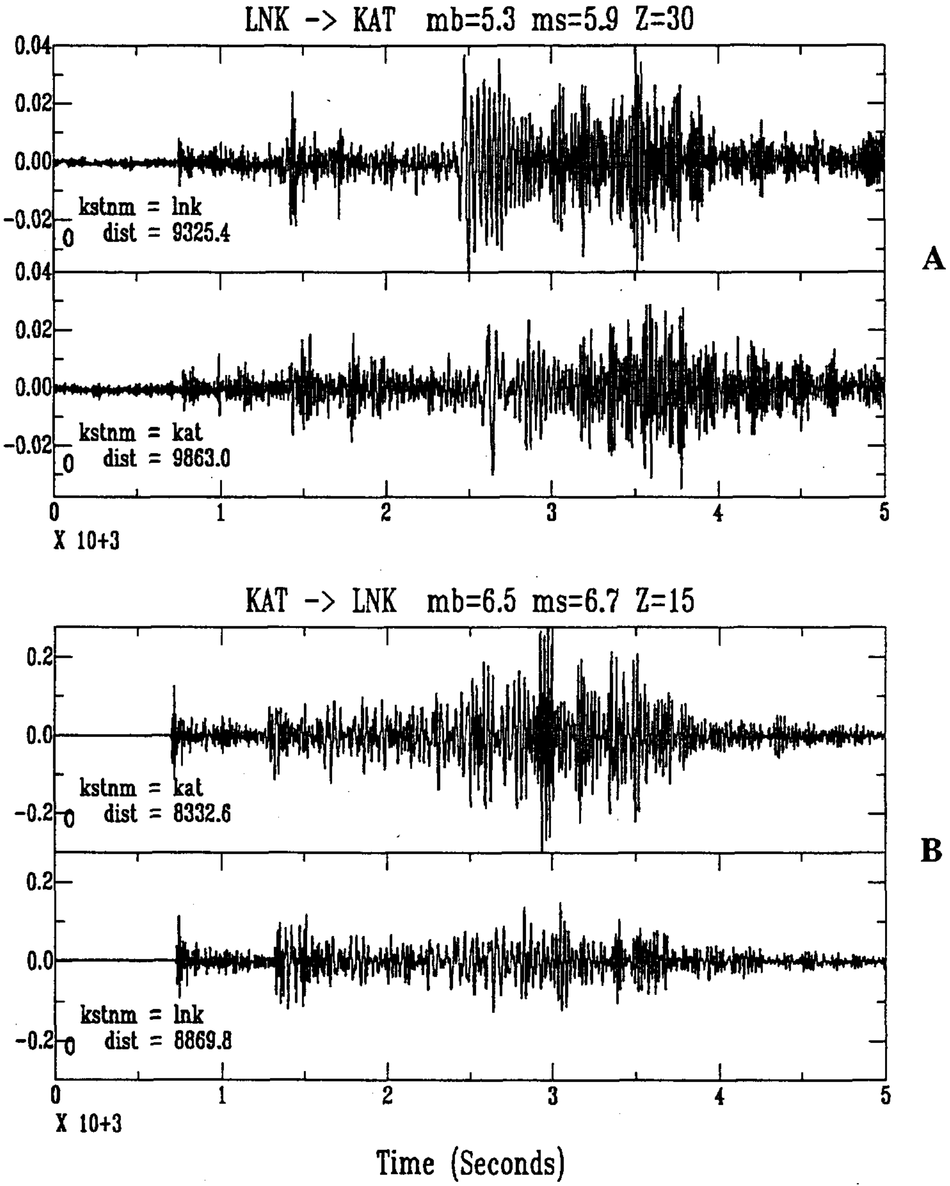
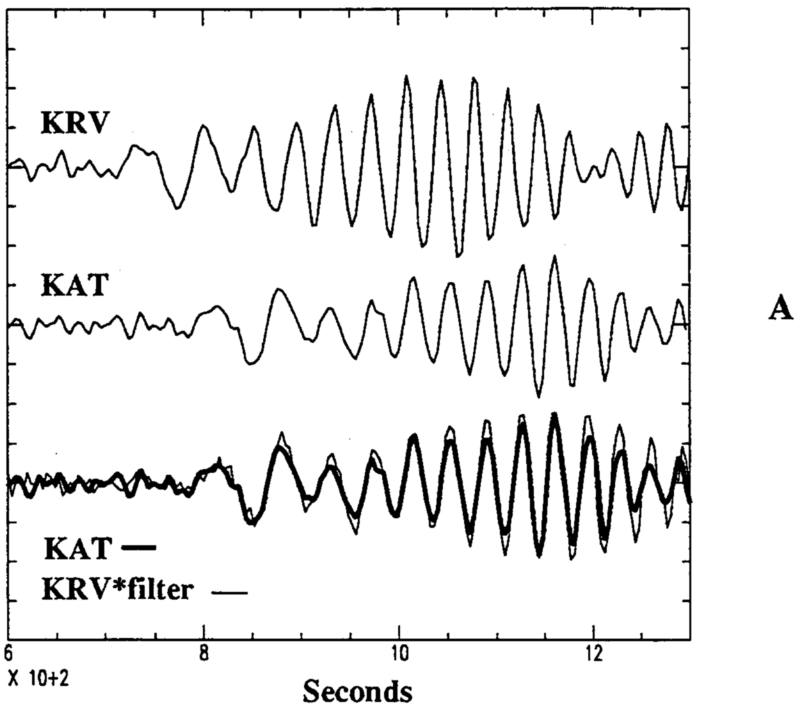


Figure3. Reversed, great circle path vertical component seismograms recorded at CSN stations LNK and KAT. The top figure (A) is a record of a mid-Atlantic ridge earthquake propagating from west to east across the south Caspian Basin, while the lower figure (B) is a larger event from the Mulucca Sea which propagates across the Basin from east to west. Both pairs show considerable degradation of the surface wave train after propagating across the south Caspian Basin. These seismograms are characteristic of all great circle path events across the central portion of the south Caspian Basin.



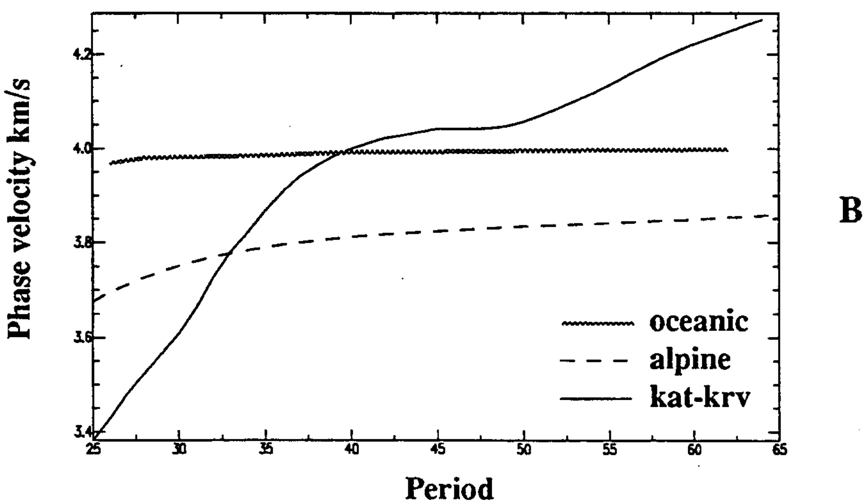


Figure 4. The upper figure (A) shows one of four common great circle path fundamental mode Rayleigh wave pairs used to compute the dispersion results shown in the lower figure (B). Also shown in (A) is the close station filtered with the resulting phase velocity transfer function. The lower figure (B) compares our preliminary results with typical oceanic (Kuo et al. 1962) and Alpine (Knopoff et al. 1966) models.